Microstructure and mechanical properties of Al-10Si alloy modified with Al-5Ti

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Abstract: The microstructure, fracture morphology and mechanical properties of Al-10Si alloy modified with Al-5Ti were analyzed and tested by optical microscopy, scanning electron microscopy, and universal electronic testing machine. Compared with unmodified Al-10Si alloy, the area fraction of α -Al phase in Al-10Si alloy modified at 740 °C increased first and then decreased with the increase of added amounts of Al-5Ti, and reached the maximum when the added amount of Al-5Ti was 0.5wt.%. When the modification temperature increased from 700 to 740 °C with Al-5Ti being fixed at 0.5wt.%, α -Al dendrites were refined obviously and the area fraction remarkably increased. Compared with unmodified Al-10Si alloy, the ultimate tensile strength and elongation of the alloy modified at 740 °C with 0.5wt.% Al-5Ti increased by 9% and 49%, respectively. The fracture surface of modified alloy predominantly exhibited ductile fracture.

Key words: Al-10Si; modification; microstructure; mechanical properties

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Al-Si alloys are widely used in aerospace, automobile, ship, household appliances and other industries due to the advantages such as low density, high strength, good corrosion resistance, good casting performance and excellent conductivity and thermal conductivity^[1-3]. Al-Si alloy parts prepared by casting method accounts for 85%–90% of the total^[4]. Hypoeutectic Al-Si alloy consists of coarse α -Al dendrites and needle-like eutectic silicon. The morphologies, size and distribution of eutectic Si together with α -Al dendrites obviously affect the mechanical properties of hypoeutectic Al-Si alloy^[5]. The coarse α -Al dendrites decrease the strength and ductility of the alloy^[6]. Needle-like eutectic Si splits α -Al matrix, resulting in the decrease of mechanical properties^[2, 7]. The refinement of α -Al dendrites and the morphology improvement of eutectic Si from needle into fibrous or short rod can improve the mechanical properties of hypoeutectic Al-Si alloy^[8, 9].

The primary α -Al phase can be refined by methods such as laser melting^[9], rapid solidification^[10], electromagnetic stirring^[11] and grain refiner addition^[7]. However, laser melting and rapid solidification, as well as electromagnetic stirring, require expensive equipment. Adding a grain refiner is a cheaper and simpler method. The most commonly used refiners are Al-Ti^[12, 13], Al-B, Al-Ti-B^[14, 15] and Al-Ti-C master alloy^[16, 17], etc. Al-Ti master alloy was first used to refine α -Al phase in pure aluminum or wrought aluminum alloy^[18]. Later it is used to refine the α -Al phase in Al-Si alloy. The modification effect of Al-Ti on aluminum alloy is unstable and fading of modification is easy to occur^[19]. The modification effect of Al-Ti-B on α -Al phase is better^[20], but trace elements (Zr, V, and Cr) would react with Al-Ti-B in Al-Si alloy to produce a “poison” phenomenon^[17, 21, 22], resulting in the deterioration of modification effect. Al-Ti-C master alloy overcomes the shortage of Al-Ti-B master alloy^[22], but the poor wet-ability between graphite and liquid Al is one of the key issues in the production of Al-Ti-C grain refiner.

To date, research mainly focused on the effect of modification on α -Al phase refining and the morphology change of eutectic Si in hypoeutectic Al-Si alloys. Little attention was paid to the influence of modification on the movement of non-equilibrium eutectic point in Al-Si

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alloy and the resulting change of the area fraction of α -Al phase, as well as the mechanical properties of hypoeutectic Al-Si alloys. In order to analyze the modification effect of titanium on Al-Si alloys and decrease the influence of other elements, Al-5Ti was used as a refiner. The microstructure and mechanical properties of Al-10Si alloy modified with Al-5Ti were investigated. The study is of significance to improve the mechanical properties of Al-Si alloy and to expand its application field in industry.

1 Experimental procedure

Al-10Si alloy was prepared using raw materials of industrial pure aluminum (99.97%, mass fraction, hereinafter), and Al-50%Si. 2000 g ingots of Al-10Si alloy were prepared as follows: 400 g Al-50%Si master alloy was placed at the bottom of a graphite crucible, and then 1,600 g pure aluminum was put on top of the Al-50%Si. The alloys were melted in a resistance furnace at 740 °C for 30 min. At last, small ingots were obtained by pouring the melt into a metal mold at room temperature.

The 200 g Al-10Si alloy was remelted in a graphite crucible furnace at 740 °C. The melting surface was covered with complex salt (mass ratio of NaCl: KCl: Na_3AlF_6 is 6:9:5) to reduce the oxidation and burning of alloy melt. Chemical analysis showed that the fluctuation of silicon content was less than 3%. To investigate the effect of added amounts of Al-5Ti on modification effect of Al-10Si alloy, 0.1, 0.3, 0.5, 0.7 and 0.9wt.% of Al-5Ti, respectively, was added in the melt and kept for 3 min. C_2Cl_6 was used for degassing treatment. To investigate the effect of temperature on modification effect of Al-10Si alloy, 200 g Al-10Si alloy was remelted and modified with 0.5wt.% of Al-5Ti at 700 °C, 740 °C and 780 °C for 3 min, respectively. Finally, the modified melt was poured into a steel mold with an inner size of

$\Phi 12 \text{ mm} \times 100 \text{ mm}$.

Metallographic samples were cut from the casting samples at a position of 10 mm from the bottom. The samples were polished and further etched with Keller's reagent. The microstructure of the samples was observed and analyzed using a Leica DIM3000 optical microscope. The area fraction of α -Al in Al-10Si alloy was measured with Photoshop software. The value was the average of three measurements. Tensile tests were carried out on specimens with 6 mm gauge diameter and 30 mm gauge length at a stretching rate of $2 \text{ mm} \cdot \text{s}^{-1}$ using a WDW-300 universal tensile testing machine and following ASTM E8 standard; the value was the average of three measurements. Characterization of fracture morphologies of the tensile samples of Al-10Si alloy was carried out with a JSM-6360LV scanning electron microscope.

2 Results and discussion

2.1 Effect of Al-5Ti addition amount on microstructure of Al-10Si alloy

Figure 1 shows the microstructures of Al-10Si alloy modified with different amounts of Al-5Ti at 740 °C. As shown in Fig. 1(a), coarse dendritic primary α -Al and eutectic microstructure are apparent in the unmodified Al-10Si alloy. The distribution of dendritic primary α -Al is uneven. The α -Al dendrites after modification with 0.1wt.% Al-5Ti are obviously refined and its amounts increases. The distribution of α -Al dendrites is more uniform. When the added amounts of Al-5Ti increases from 0.1wt.% to 0.5wt.%, the amount of α -Al dendrites increased gradually. After the added amounts of Al-5Ti is more than 0.5wt.%, the amount of α -Al dendrites decreases and the α -Al dendrites become coarse with the increasing of Al-5Ti.

Fig. 1: Microstructures of Al-10Si modified with different amounts of Al-5Ti: (a) 0.0wt.%; (b) 0.1wt.%; (c) 0.3wt.%; (d) 0.5wt.%; (e) 0.7wt.%; (f) 0.9wt.%

Table 1 shows the quantitative analysis of area fraction of α -Al phase in Al-10Si alloy modified with different amounts of Al-5Ti at 740 °C. As shown in Table 1, the area fraction of α -Al phase increases first and then decreases with increasing addition

of Al-5Ti from 0.1 to 0.9wt.%. The area fraction of α -Al phase reaches the maximum when the added amount of Al-5Ti is 0.5wt.%, which is in agreement with Fig. 1.

Table 1: Area fraction of primary α -Al in Al-10Si modified with different amounts of Al-5Ti

Al-5Ti (wt.%)	0	0.1	0.3	0.5	0.7	0.9
Area fraction of primary α -Al (%)	41.4	47.5	51.0	52.8	46.3	45.4

Eutectic Al-Si alloy modified with Al-3P or Al-5Ti could change the non-equilibrium eutectic point of Al-Si phase diagram^[23,24], so hypoeutectic Al-Si alloy modified with Al-5Ti could also change the non-equilibrium eutectic point of Al-

Si system. The variation of the area fraction of α -Al phase in modified Al-10Si alloy can be explained by the movement of non-equilibrium eutectic point of Al-Si binary system, as shown in Fig. 2.

Fig. 2: Schematic of eutectic point variation of Al-Si alloy modified with different amounts of Al-5Ti: (a) less than 0.5wt.% Al-5Ti; (b) more than 0.5wt.% Al-5Ti

In Fig. 2, C_0 is the equilibrium eutectic point in Al-Si phase diagram, $C_{0.1}$, $C_{0.3}$, $C_{0.5}$, $C_{0.7}$ and $C_{0.9}$ represent non-equilibrium eutectic points, corresponding to the melt modified with 0.1, 0.3, 0.5, 0.7 and 0.9wt.% Al-5Ti, respectively at 740 °C.

Modification of Al-Si alloy with Al-5Ti had little direct impact on the nucleation and growth of primary Si. When the added amounts of Al-5Ti was less than 0.5wt.%, the effect of modifier on the temperature of liquid Al-Si alloy was also very small. The undercooling degree of hypereutectic Al-Si alloy was almost at a certain value after modification with a small amount of Al-5Ti, as shown in Fig. 2(a). Al_3Ti particles in Al-5Ti master alloy could act as the effective nucleation core of primary α -Al phase in hypoeutectic Al-Si alloy, resulting in an obvious decrease in undercooling degree of hypoeutectic Al-Si alloy^[24,25]. The non-equilibrium eutectic point of the hypoeutectic Al-Si alloy would shift to the right because of the decrease of undercooling degree. With the increase of the added amounts of Al-5Ti, the number of Al_3Ti particles increased, further resulting in the decrease of undercooling degree of hypoeutectic Al-Si alloy, as shown in Fig. 2(a). According to Lever's law, the area fraction of α -Al phase in Al-10Si alloy would increase with the added amounts of Al-5Ti.

When the added amounts of Al-5Ti was more than 0.5wt.%, the effect of modifier on the temperature of Al-Si alloy is shown in Fig. 2(b). The more the added amounts of Al-5Ti, the more the temperature of alloy decreased, resulting in the decrease of the cooling rate of the alloy, and finally, the undercooling degree of Al-Si alloy decreased. In addition, the undercooling degree of hypoeutectic Al-Si alloy was much lower than that of hypereutectic Al-Si alloy due to the modification effect of Al-5Ti, as shown in Fig. 2(b). When the added amounts of Al-5Ti were from 0.5wt.% to 0.9wt.%, the non-equilibrium eutectic point of Al-Si alloy would also move to the right. With the increase of the added amounts of Al-5Ti, the moving distance of the non-equilibrium eutectic point to the right would be decreased. As a result, $C_{0.7}$ is on the left side of $C_{0.5}$ and $C_{0.9}$ is on the left side of $C_{0.7}$. According to Lever's law, when the added amounts of Al-5Ti increased from 0.5wt.% to 0.9wt.%, the area fraction of α -Al phase in Al-10Si alloy decreased, as shown in Table 1.

2.2 Effect of modification temperature on microstructure of Al-10Si alloy

Figure 3 shows the microstructure of Al-10Si alloy modified with 0.5wt.% Al-5Ti at different temperatures. When the modification

Fig. 3: Microstructures of Al-10Si alloy modified with 0.5wt.% Al-5Ti at different temperatures: (a) 700 °C; (b) 740 °C; (c) 780 °C

temperature was 700 °C, the size of α -Al phase was relatively larger and its amount was less. When the temperature increased to 740 °C, the α -Al phase was obviously refined. The area fraction of α -Al phase increased significantly and distributed more uniformly. When the temperature reached 780 °C, the α -Al phase was further refined and its number was further increased compared with that in Al-10Si alloy modified at 740 °C. With the increase of temperature, the α -Al phase became finer and finer, the area fraction of the phase became greater and greater. When the temperature increased from 700 to 740 °C, the refining extent of the α -Al phase was more obvious and the increased amount of the phase was much more than that from 740 to 780 °C.

The quantitative analysis results of the area fraction of α -Al phase in Al-10Si alloy modified with 0.5wt.% Al-5Ti at different temperatures are shown in Table 2. It was clearly seen from Table 2 that the area fraction of α -Al phase obviously increased when the modification temperature increased from 700 to 740 °C, and increased a little when the temperature further increased from 740 to 780 °C. From the point of view of the area fraction of α -Al phase, the most suitable modification temperature was 740 °C.

Table 2: Area fraction of primary α -Al in Al-10Si alloy modified with 0.5wt.% Al-5Ti at different temperatures

Modification temperature (°C)	Area fraction of primary α -Al (%)
700	43.3
740	52.8
780	53.7

The area fraction of α -Al phase in modified Al-10Si alloy changed with the variation of modification temperature. This could be explained through Fig. 4, which is a schematic diagram of eutectic point variation of Al-Si alloy modified with 0.5wt.% Al-5Ti at different temperatures. C_0 is the position of equilibrium eutectic point of Al-Si alloy. C_{700} , C_{740} and C_{780} are the non-equilibrium eutectic points of Al-Si alloy modified at 700 °C, 740 °C and 780 °C, respectively. With the increase of modification temperature, the cooling rate of the alloy liquid became more rapid, and the undercooling degree of the alloy increased. Because Al-5Ti has little direct modification effect on hypereutectic Al-Si alloy, it has no influence on

Fig. 4: Schematic of eutectic point variation of Al-Si alloy modified with 0.5wt.% Al-5Ti

the undercooling degree of hypereutectic Al-Si alloy. Al-5Ti has great modification effect on hypoeutectic Al-Si alloy, resulting in an obvious decrease of the undercooling degree of hypoeutectic Al-Si alloy. The synergetic effect of Al-5Ti modification and the temperature makes the non-equilibrium eutectic point of Al-Si alloy move to the right. With the increase of temperature, the moving distance of the non-equilibrium eutectic point to the right increased. According to Lever's law, the area fraction of primary α -Al phase in modified Al-10Si alloy would increase.

2.3 Mechanical properties of modified Al-10Si alloy

Table 3 shows the ultimate tensile strength and elongation of unmodified Al-10Si alloy and the alloy modified with 0.5wt.% Al-5Ti at 740 °C. As shown in Table 3, the ultimate tensile strength and elongation of unmodified Al-10Si alloy are 176 MPa and 5.1%, respectively. After modification with 0.5wt.% Al-5Ti, the tensile properties of the alloy were obviously improved to 192 MPa and 7.6%, respectively.

The improvement of mechanical properties of the modified Al-10Si alloy is closely related to microstructure. Compared with unmodified Al-10Si alloy, the area fraction of the α -Al phase increased from 41.4% to 52.8% after being modified with 0.5wt.% Al-5Ti, resulting in a significant increase of elongation. In addition, the ultimate tensile strength of the Al-10Si alloy also increased due to the refinement of the α -Al phase. The

Table 3: Mechanical properties of Al-10Si alloy before and after modification with 0.5wt.% Al-5Ti

Temperature (°C)	Ultimate tensile strength (MPa)		Elongation (%)	
	Unmodified alloy	Modified alloy	Unmodified alloy	Modified alloy
740	176±6	192±8	5.1±0.5	7.6±0.2

refinement of the α -Al indicates that the area of phase interface or grain boundaries increases, which could hinder the slip of dislocations and prevent the stress concentration.

Figure 5 shows the fracture morphology of the tensile samples of unmodified Al-10Si alloy and the alloy modified with 0.5wt.% Al-5Ti at 740 °C. As can be seen from Fig. 5(a), large cleavage

platforms existed on the fractured surface of unmodified Al-10Si alloy. After modification with 0.5wt.% Al-5Ti, the size of cleavage platform in fracture surface of Al-10Si alloy decreased obviously, and the number of dimples and tear edges increased, as shown in Fig. 5(b). The fracture surface of the modified alloy exhibits a predominantly ductile fracture.

Fig. 5: Fracture morphology of tensile samples of Al-10Si: (a) unmodified; (b) modified with 0.5wt.% Al-5Ti at 740 °C

3 Conclusions

(1) The area fraction of the α -Al phase in Al-10Si alloy increases first and then decreases with the increase of added amounts of Al-5Ti at 740 °C. When the added amount of Al-5Ti is 0.5wt.%, the area fraction of α -Al phase reaches the maximum.

(2) The α -Al dendrites are obviously refined and the area fraction of α -Al phase obviously increases when the modification temperature increases from 700 to 740 °C with addition of 0.5wt.% Al-5Ti. From the point of view of the area fraction of α -Al phase, the most suitable modification temperature is 740 °C.

(3) Compared with unmodified Al-10Si alloy, the ultimate tensile strength and elongation of Al-10Si alloy modified with 0.5wt.% Al-5Ti at 740 °C are increased by 9% and 49%, respectively. The fracture surface of the modified alloy exhibits a predominantly ductile fracture.

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